

Direct numerical simulation of 3D particle motion in an evaporating liquid film[†]

Hochan Hwang and Gihun Son^{*}

Department of Mechanical Engineering, Sogang University, 35 Baekbeom-ro, Mapo-gu, Seoul 04107, Korea

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Abstract

A direct numerical simulation method is developed for 3D particle motion in liquid film evaporation. The liquid-gas and fluid-solid interfaces are tracked by a sharp-interface Level-set (LS) method, which includes the effects of evaporation, contact line and solid particles. The LS method is validated through simulation of the interaction between two particles falling in a single-phase fluid. The LS based DNS method is applied to computation of the particle motion in liquid film evaporation to investigate the particle-interface and particle-particle interactions.

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Keywords: Evaporation; Level- set method; Particle motion

1. Introduction

The particle motion in an evaporating liquid film is very important in fabrication of particulate microstructures [1]. Its predictive models were developed in several studies using the particle concentration [2-5], but the models have a limitation in analysis of the interaction between a particle and a fluid, a liquid-gas interface and other particles. Recently, Direct numerical simulation (DNS) methods were proposed for the particle interactions.

Glowinski et al. [6], Sharma and Patankar [7], and Apte et al. [8] performed DNS of particle-fluid and particle-particle interactions in a single-phase fluid employing a Fictitious domain (FD) method, where the particles were treated as the surrounding fluid region.

Mirzaii and Passandideh-Fard [9] combined the FD method and the Volume-of-fluid (VOF) method to investigate the particle-particle and particle-interface interactions. They assumed the particles as high-viscosity fluid and used a Piecewise linear interface calculation (PLIC) algorithm for reconstructing the interface. The PLIC VOF method is much complicated to implement in the region including three phases of liquid, gas and solid.

Fujita et al. [10] coupled an Immersed boundary (IB) method for a solid particle to a diffuse-interface Level-set (LS) method for a liquid-gas interface to compute the particle interactions in liquid evaporation. They assumed the vaporization rate constant instead of obtaining it from the conservation

*Corresponding author. Tel.: +82 2 705 8641, Fax.: +82 2 712 0799

equations of energy and vapor concentration. Subsequently, Hwang and Son [11] applied a sharp-interface LS method to DNS of particle motion in microdroplet evaporation introducing two LS functions for the liquid-gas and fluid-solid interfaces.

In this study, we further extend the LS method to compute 3D particle motion in an evaporating liquid film and investigate the associated particle-interface and particle-particle interactions.

2. Numerical analysis

We employ the LS method developed in our previous studies [11-13] for droplet evaporation and particle motion. The gas is assumed as an ideal mixture of air and vapor whereas the liquid as a pure substance.

The liquid-gas interface is represented by the LS function ϕ , which is determined to be a signed distance from the interface: $\phi \le 0$ for gas phase and $\phi > 0$ for liquid phase. The fluid-solid interface of an immersed solid particle is tracked by another LS function ψ , which is calculated as a signed distance from the fluid-solid interface: $\psi \le 0$ for solid phase and $\psi > 0$ for fluid phase. A typical example of the LS contours for the case where a particle is partly immersed is plotted in Fig. 1. **Numerical analysis**
We employ the LS method developed in our previous stud-
[11-13] for droplet evaporation and particle motion. The
s is assumed as an ideal mixture of air and vapor whereas
liquid as a pure substance.
T

In this work, assuming solid spheres as particles, ψ is expressed as

$$
\psi(\mathbf{x},t) = |\mathbf{x} - \mathbf{x}_p(t)| - d_p / 2 \tag{1}
$$

where \mathbf{x}_n is the position vector of particle centroid and d_n

E-mail address: gihun@sogang.ac.kr

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where a particle is partly immersed. The blue and red lines denote ϕ and ψ contours, respectively.

is the diameter of particles.

Assuming the solid domain is occupied by a high-viscosity non-evaporating fluid, the conservation equations of mass, momentum and energy for the liquid and gas phases and vapor mass fraction (Y_v) for the gas phase can be written as [11-13] ² ^ˆ [()] + *^p ^m* ^ˆ 0.1 $\frac{(1 - T_{v,f})}{n_g}$
 $\frac{N_{v,f}}{N_{v,f}} = \frac{M_{v,f}p_{v,m}(T_f)}{M_{v,f}p_{v,m}(T_f) + M_{s}[p_{v} - p_{v,m}(T_f)]}$

are a particle is partly immersed. The blue and red lines denote ϕ

w contours, respectively.

We contours, respectively.

the d 0.1 0.2 0.3

x
 $y_{v,J} = \frac{M_{v,P_{v,ss}}(T_i)}{M_{v,P_{v,ss}}(T_i) + M_{s}[P_{\infty} - P_{v,ss}(T_i)]}$.

typical example of level-set (ϕ, ψ) contours for the case

contours, respectively.

contours, respectively.

The LS function including ϕ 0.1 **a** $u = t_{v,f}$) $u_{v,m}(T_i) + M_z[D_e - P_{r,m}(T_i)]$

1. A typical example of level-set (ϕ, ψ) contours for the case
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(1.1 A typical example of level-set (ϕ, ψ) contours for the case
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 $v = \frac{M_x p_{x,\omega}(T_x)}{M_y p_{x,\omega}(T_x) + M_x [p_x - p_{x,\omega}(T_x)]}$. (10)

1. A typical example of level-set (b, y) contours for the case
 ψ contours, respectively.
 ψ 1. A typical example of levelset of $V_{i,j} = \frac{V_{i,j}}{M_{i,j}} = \frac{V_{i,j}}{M_{i,j}} = \frac{V_{i,j}}{P_{i,j}M_{i,j}} = \frac{V_{i,j}}{P_{i,j}M_{i,j}}$ (10)

if ψ contours, respectively,
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 ψ contours, respectively,
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evaluation y contours, respectively.

The LS function including $\phi = 0$ for the interface is advanced as

summing he solid domain is occupied by a high-viscosity

evaporating fluid, the conservation equations of mass,
 $\frac{\partial \phi}{\partial \tau}$

$$
\nabla \cdot \mathbf{u} = \alpha_{\psi} \beta \dot{m} \mathbf{n} \cdot \nabla \alpha_{\phi}
$$
 (2)

$$
\hat{\rho}\frac{\partial \mathbf{u}}{\partial t} = -[\nabla p + \alpha_{\psi}(\sigma \kappa - \beta \dot{m}^2) \nabla \alpha_{\phi}] + \nabla \cdot \hat{\mu} \nabla \mathbf{u} + \mathbf{f}
$$
\n(3)

$$
\widehat{(\rho c)}\frac{\partial T}{\partial t} = -(\widehat{\rho c})\mathbf{u}_f \cdot \nabla T + \nabla \cdot \widehat{\lambda}\nabla T \quad \text{if } \phi \neq 0 \text{ or } \psi \leq 0 \tag{4}
$$

$$
T = T_1 \qquad \text{if } \phi = 0 \text{ and } \psi > 0 \qquad (5)
$$

$$
\frac{\partial I_{\nu}}{\partial t} = -\mathbf{u}_{g} \cdot \nabla Y_{\nu} + \nabla \cdot \hat{D}_{\nu} \nabla Y_{\nu} \quad \text{if } \phi < 0 \text{ and } \psi > 0 \quad (6)
$$

momentum and energy for the liquid and gas phases and va-
\npartition
$$
(Y_x)
$$
 for the gas phase can be written as
\n
$$
\int \frac{\partial \phi}{\partial r} = \cos \theta_x - \mathbf{n}_x \cdot \nabla \phi
$$
 if $\psi \le 0$ \n
$$
\int (12)
$$
\n
$$
\nabla \cdot \mathbf{u} = \alpha_{\varphi} \beta \dot{m} \mathbf{n} \cdot \nabla \alpha_{\phi}
$$
\n
$$
\frac{\partial \mu}{\partial t} = -(\nabla \rho + \alpha_{\varphi} (\cos \psi - \beta \dot{m})^2 \nabla \alpha_{\phi} + \nabla \cdot \dot{\lambda} \nabla \mathbf{r} + \mathbf{r} \cdot \dot{\lambda} \nabla \mathbf{r}
$$

Here, the subscript *f* denotes the gas phase (*g*) for $\phi \le 0$ and the liquid phase (*l*) for $\phi > 0$. The effective properties $\hat{\rho}$, $\hat{\mu}$, $\hat{\lambda}$ and \hat{D}_y are interpolated by using a fraction function F_{ϕ} [13]. The temperature T_{I} , the vapor fraction $Y_{v,I}$ and the 929~3934

ss the gas phase (g) for $\phi \le 0$ and

0. The effective properties $\hat{\rho}$,

ated by using a fraction function

, the vapor fraction $Y_{v,l}$ and the

the interface ($\phi = 0$) are simul-

following mass and energy evaporation mass flux \dot{m} at the interface ($\phi = 0$) are simultaneously calculated from the following mass and energy balances and the thermodynamic relation logy 30 (9) (2016) 3929-3934

ubscript f denotes the gas phase (g) for $\phi \le 0$ and

aase (l) for $\phi > 0$. The effective properties $\hat{\rho}$,
 \hat{D}_v are interpolated by using a fraction function

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the subscript f denotes the gas phase (g) for $\phi \le 0$ and

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and \hat{D}_y are interpolated by using a fraction function

The tem subscript *f* denotes the gas phase (*g*) for $\phi \le 0$ as

ohase (*l*) for $\phi > 0$. The effective properties \hat{D}_y are interpolated by using a fraction function

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ma *and Technology 30 (9) (2016) 3929-3934*

Here, the subscript *f* denotes the gas phase (*g*) for $\phi \le 0$ and
 i liquid phase (*l*) for $\phi > 0$. The effective properties $\hat{\rho}$,
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e subscript *f* denotes the gas phase (*g*) for $\phi \le 0$ and

phase (*l*) for $\phi > 0$. The effective properties $\hat{\rho}$,

d \hat{D}_v are interpolated by using a fraction function

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the subscript f denotes the gas phase (g) for $\phi \le 0$ and

1 phase (l) for $\phi > 0$. The effective properties $\hat{\rho}$,

and \hat{D}_v are interpolated by using a fraction function

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ubscript f denotes the gas phase (g) for $\phi \le 0$ and

ase (f) for $\phi > 0$. The effective properties $\hat{\rho}$,
 $\hat{\partial}$, are interpolated by using a fraction function

temperature T_i , the vapo *so (9) (2016) 3929-3934*

script *f* denotes the gas phase (*g*) for $\phi \le 0$ and
 e (*l*) for $\phi > 0$. The effective properties $\hat{\rho}$,

are interpolated by using a fraction function

spress flux *in* at the interfac *v v v v (b) (a) (b) (a) v (d) s <i>v s s (g) for* $\phi \le 0$ and liquid phase *(l)* for $\phi > 0$. The effective properties $\hat{\rho}$, $\hat{\lambda}$ and \hat{D}_{ν} are interpolated by using a fraction fun *Technology 30 (9) (2016) 3929-3934*
 e, the subscript *f* denotes the gas phase (g) for $\phi \le 0$ and
 uid phase (*l*) for $\phi > 0$. The effective properties $\hat{\rho}$,

and \hat{D}_v are interpolated by using a fraction 9) (2016) 3929-3934

tt f denotes the gas phase (g) for $\phi \le 0$ and

for $\phi > 0$. The effective properties $\hat{\rho}$,

interpolated by using a fraction function

ature T_i , the vapor fraction $Y_{v,i}$ and the

interpolated Exploration products are gas phase (*x*) for $\phi > 0$. The effective properties $\hat{\rho}$,

in and \hat{D}_x are interpolated by using a fraction function

[13]. The temperature T_i , the vapor fraction $Y_{i,j}$ and the

prora or all ω is the method of the method of the space interesting the method in the boration mass flux *in* at the interface ($\phi = 0$) are simulously calculated from the following mass and energy bal-
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temperature T_i , the vapor fraction $Y_{v,f}$ and the

mass flux \dot{m} at the interface $(\phi = 0)$ are simul-

leulated from the following mass and energy bal-

teherm 213). The temperature T_i , the vapor fraction $Y_{i,j}$ and the portion mass flux \dot{m} at the interface ($\phi = 0$) are simul-
eously calculated from the following mass and energy bal-
essand the thermodynamic relation
 $\$

$$
\dot{m} = \frac{\mathbf{n} \cdot \rho_g \hat{D}_v \nabla Y_v}{(1 - Y_{v,t})} = \frac{\mathbf{n} \cdot [(\hat{\lambda} \nabla T)_{\phi > 0} - (\hat{\lambda} \nabla T)_{\phi < 0}]}{h_{te}} \tag{9}
$$

$$
Y_{v,I} = \frac{M_{v} p_{v,sat}(T_{I})}{M_{v} p_{v,sat}(T_{I}) + M_{a}[p_{\infty} - p_{v,sat}(T_{I})]}.
$$
\n(10)

The LS function including $\phi = 0$ for the interface is advanced as

$$
\frac{\partial \phi}{\partial t} = -\mathbf{U} \cdot \nabla \phi \qquad \text{if } \psi > 0 \tag{11}
$$

$$
\frac{\partial \phi}{\partial \tau} = \cos \theta_s - \mathbf{n}_s \cdot \nabla \phi \qquad \text{if } \psi \le 0 \tag{12}
$$

where the interface velocity **U** and the unit normal vector is **n***^s* pointing into the solid domain are expressed as

$$
J = \mathbf{u}_1 + \dot{m}\mathbf{n} / \rho_1 \tag{13}
$$

$$
\mathbf{I}_s = -\nabla \psi / |\nabla \psi| \,. \tag{14}
$$

 $\dot{m} = \frac{\mathbf{n} \cdot \rho_s \hat{D}_s \nabla Y_s}{(1 - Y_{v,t})} = \frac{\mathbf{n} \cdot [(\hat{\lambda} \nabla T)_{\phi=0} - (\hat{\lambda} \nabla T)_{\phi=0})}{h_{lg}}$ (9)
 $Y_{v,t} = \frac{M_{v} p_{v,sut}(T_t)}{M_{v} p_{v,sut}(T_t) + M_{s} [p_{\phi} - p_{v,sut}(T_t)]}$. (10)

The LS function including $\phi = 0$ for the interface is $Y_{y.x} = \frac{M_{y.P_{y, sat}}(T_i)}{M_{y.P_{y, sat}}(T_i) + M_{\theta}[P_{\infty} - P_{y, sat}(T_i)]}$. (10)

The LS function including $\phi = 0$ for the interface is ad-

acced as
 $\frac{\partial \phi}{\partial t} = -U \cdot \nabla \phi$ if $\psi > 0$ (11)
 $\frac{\partial \phi}{\partial \tau} = \cos \theta, -\mathbf{n}_s \cdot \nabla \phi$ if The contact angle condition specified at contact line is implemented in the entire solid domain by using Eq. (12), which is iteratively solved as ed as
 $\frac{\phi}{t} = -U \cdot \nabla \phi$ if $\psi > 0$ (11)
 $\frac{\phi}{\tau} = \cos \theta_s - \mathbf{n}_s \cdot \nabla \phi$ if $\psi \le 0$ (12)

re the interface velocity U and the unit normal vector is

pointing into the solid domain are expressed as
 $= \mathbf{u}_1 + \dot{m} \cdot \$ **s** for $\frac{\partial \phi}{\partial t} = -\mathbf{U} \cdot \nabla \phi$ if $\psi > 0$ (11)
 $\frac{\partial \phi}{\partial \tau} = \cos \theta, -\mathbf{n}_s \cdot \nabla \phi$ if $\psi \le 0$ (12)
 $\frac{\partial \phi}{\partial \tau} = \cos \theta, -\mathbf{n}_s \cdot \nabla \phi$ if $\psi \le 0$ (12)

or energies the interface velocity **U** and the unit normal $\nabla \phi$ if $\psi > 0$ (11)
 $\partial_z - \mathbf{n}_z \cdot \nabla \phi$ if $\psi \le 0$ (12)

terface velocity U and the unit normal vector is

into the solid domain are expressed as
 $|\mathbf{n}/\rho_i|$ (13)
 $\sqrt{|\nabla \psi|}$. (14)

ct angle condition specified where the interface velocity U and the unit normal vector is
 n, pointing into the solid domain are expressed as

U = **u**_{*t*} + \dot{m} 1 (*1*)
 n_{*s*} = - $\nabla \psi / |\nabla \psi|$. (13)

The contact angle condition specified The the interface velocity U and the unit normal vector is
pointing into the solid domain are expressed as
 $J = \mathbf{u}_1 + \sin h / \rho_1$ (13)
 $I = -\nabla \psi / |\nabla \psi|$. (14)
the contact angle condition specified at contact line is im-
e ere the interface velocity U and the unit normal vector is

pointing into the solid domain are expressed as
 $U = u_t + \sinh/\rho_t$ (13)
 $n_x = -\nabla \psi / |\nabla \psi|$. (14)

The contact angle condition specified at contact line is im-

me

$$
\frac{\phi^{m+1} - \phi^m}{\Delta \tau} = \cos \theta_s - \mathbf{n}_s \cdot \nabla \phi^m \qquad \text{if } \psi \le 0.
$$
 (15)

Here, the superscript *m* denotes the iteration step. The LS

$$
\frac{\partial \phi}{\partial \tau} = \frac{\phi}{\sqrt{\phi^2 + h^2}} (1 - |\nabla \phi|) \quad \text{if} \quad |\phi| \ge h/2 \tag{16}
$$

where *h* is a grid spacing.

To impose the rigid body motion, the velocity inside the solid domain is modified as

$$
\mathbf{u} = \mathbf{u}_p + \mathbf{\omega}_p \times (\mathbf{x} - \mathbf{x}_p) \tag{17}
$$

The contact angle condition specified at contact line is im-
mented in the entire solid domain by using Eq. (12), which
teratively solved as
 $\frac{\phi^{n+1} - \phi^{n}}{\Delta \tau} = \cos \theta, -\mathbf{n} \cdot \nabla \phi^n$ if $\psi \le 0$. (15)
Here, the superscr where u_p and ω_p of the particle centroid are determined from the following conservation condition of the linear and angular momenta in each particle domain [7], Here, the superscript *m* denotes the iteration step. The LS

action is reinitialized as
 $\frac{\partial \phi}{\partial \tau} = \frac{\phi}{\sqrt{\phi^2 + h^2}} (1 - |\nabla \phi|)$ if $|\phi| \ge h/2$ (16)

ore *h* is a grid spacing.

To impose the rigid body motion, the vel

$$
\mathbf{u}_p = \frac{1}{V_p} \int \mathbf{u} \, dV_p \tag{18}
$$

$$
\mathbf{\omega}_p = \frac{\rho_p}{I_p} \int (\mathbf{x} - \mathbf{x}_p) \times \mathbf{u} \, dV_p \tag{19}
$$

where V_p is the particle volume and I_p is the moment of inertia of the particle.

To treat particle-particle collision, a special numerical treatment reported by Diaz-Goano et al. [14] is used so that the particle should not overlap the other particle.

3. Results and discussion

3.1 Two-particle sedimentation a non-evaporating fluid

The LS formulation including the effect of particle-particle interaction is tested through a 3D computation of two particles falling in a single-phase fluid under gravity, whose numerical result was presented by Apte et al. [8]. The computational domain is chosen as a rectangular region of $\[\omega_{\tau}\] = \frac{\rho_{\nu}}{I_{\nu}}\int (\mathbf{x}-\mathbf{x}_{\tau}) \times \mathbf{u} \, dV_{\nu}$ (19)

where V_{τ} is the particle volume and I_{ν} is the moment of

The treat particle particle collision, a special numerical

reatment reported by Diaz-Groan cal particles whose centers are initially positioned at *x* = (*x*_p + (*x*) is the moment of the particle volume and *I_r* is the moment of the particle volume and *I_r* is the moment cord to the particle coulom tend to particle coulom tend the particle showed ph the other condition is imposed at the boundaries. We use the following where r_s , is the particle countre and t_s is the moment of
treatment reported by Diaz-Gouno et al. [14] is used so that
treatment reported by Diaz-Gouno et al. [14] is used so that
the particle should not overlap the e metrion of particle particle collision, a special numerical

To treat particle-particle collisions at the particle should not overlap the other particle.

The LS formulation including the effect of particle-particle corre 10 the at patten-gradient contours on, a special numerical
reathern treported by Diaz-Goano et al. [14] is used so that
the particle should not overlap the other particle.
3. **Results and discussion**
3. Two-particle sedi itematic reporting of the state of the state of the particle and discussion

a **http://wiscosity Data viscosity of the particle state and discussion**

a **3.1 Two-particle sellimentation a non-evaporating fluid**

The LS fo a high viscosity non-evaporating fluid of $\mu = 10^3 \mu$. The particles and fluid are initially stationary. The computation is **3. Results and discussion**
 $\begin{array}{c}\n\text{3.1 Two-particle sedimentation a non-evaporating fluid} \\
\text{in the LS formulation including the effect of particle-particle\n} \end{array}$ Clear alternation including the effect of particle-particle

clear falling in a single-phase fluid under gravity, whose numerical results of **S. Results and unceded with a non-evaporating fluid

The LS formulation in a non-evaporating fluid

interaction is tested through a 3D computation of two parti-

ties falling in a single-phase fluid under gravity, whose** particle interaction are plotted in Figs. 2 and 3. As the particle velocities increase with gravity, vortex flows are induced around the particles and the upper particle falls faster in the wake region created by the lower particle. This results in a decrease in the distance between the two particles. The present prediction of the particle sedimentation positions and velocities in the vertical direction shows a good agreement with the numerical results of Apte et al. [8]. (1/6) cm. In the LS formulation, the solid region is treated as a relation of $M_4 = 1$, $M_2 = 0$, $M_3 = 0$, $M_4 = 0$, $M_5 = 0$, $M_6 = 1/(44)$ mm and time step of $M_7 = 1$, $M_8 = 1/16$, $M_9 = 1/16$, $M_1 = 0$, $M_2 = 0$, M_3 particles and fluid are initially stationary. The computation is

conducted with a mesh size of $h = (1/64)$ cm and at time step

of $\Delta t = 0.5$ ms. The numerical results for the particle

velocities increase with gravity, v conducted with a mesh size of $h = (1/64)$ cm and a time step
of $\Delta t = 0.5$ and $\Delta t = 0.7$ and the particle wallocal enteration are photos are induc increase with grayity, vortex flows are induced

increase with gravity, vortex flows are induced

in the distance between the two particle. This results in a

in the distance between the two particles. The present

of of ocities increase with gravity, vortex flows are induced

und the particle fails faster in the

lever grain crease in the distance between the two particle. This results in a

lever grain of the particle sedimentation posi and the particles and the upper particle falls faster in the

region created by the lower particle. This results in a

exage in the distance between the two particles. The present

the particle such the two-particles in t

3.2 Particle motion in an evaporating liquid film

The LS method is applied to DNS of particle motion in an evaporating liquid film. The computational domain is chosen *F* paradellar and weight paradellar and state in the state of the policies of the following varieties. The present

in the distance between the two particles. The present
 $\frac{2}{3}$ and of the particle sedimentation posi *y* be lower particle. This results in a

ance between the two particles. The present

article sedimentation positions and veloci-

Frection shows a good agreement with the

⁷ Apte et al. [8].
 in an evaporating liquid Re region created by the lower particle. This results in a

recess in the distance between the vaparities. The present

recess in the particle sedimentation positions and veloci-

sin the vertical direction shows a good a

$$
\mathbf{u} = 0, \ T = T_w, \ \frac{\partial Y_v}{\partial x} = 0, \ \frac{\partial \phi}{\partial x} = \pm \cos \theta_{sw} \ \text{at} \ x = \pm 3.2 \ \mu \text{m} \tag{20}
$$

$$
\mathbf{u} = 0, \ T = T_w, \ \frac{\partial Y_v}{\partial y} = 0, \ \frac{\partial \phi}{\partial y} = -\cos \theta_{bw} \quad \text{at} \quad y = 0 \tag{21} \qquad \sigma = 7.2 \times 10^{-10}
$$

where the contact angle θ_{w} formed on the contact line can t vary dynamically between θ_a and θ_r , which was described We use in Refs. [12, 13, 15, 16].

We choose the following water and air properties:

Fig. 2. 3D numerical results of two-particle sedimentation in a nonevaporating fluid.

Fig. 3. 3D numerical results for two-particle sedimentation in a nonevaporating fluid: (a) Particle positions; (b) particle velocities in the vertical direction.

t(s)
\n*t*(s)
\nof particle motion in an
\national domain is chosen
\n*μm* and
$$
0 \le y \le 6.4 \mu m
$$
.
\n*μm*, the open boundary
\n $μm$, the open boundary
\n $ρ_t = 997 \text{ kg/m}^3$, $ρ_s = 1.18 \text{ kg/m}^3$, $ρ_s = 997 \text{ kg/m}^3$,
\n $ρ_t = 4.18 \times 10^{-3} \text{ J/kgK}$, $ε_s = 1.01 \times 10^{-3} \text{ J/kgK}$, $ε_s = 318 \text{ J/kgK}$,
\n $μ_t = 8.91 \times 10^{-4} \text{ Pas}$, $μ_s = 1.85 \times 10^{-5} \text{ Pas}$, $D_s = 2.6 \times 10^{-5} \text{ m}^2$,
\n $θ_{sw}$ at $x = \pm 3.2 \mu m$ (20)
\n $λ_t = 0.595 \text{ W/mK}$, $λ_s = 2.55 \times 10^{-2} \text{ W/mK}$, $λ_s = 31 \text{ W/mK}$,
\n $θ_{bw}$ at $y = 0$
\n(21)
\n $σ = 7.2 \times 10^{-2} \text{ N/m}$ and $θ_s = 30^\circ$.
\nThe saturated-vapor pressure is evaluated as a function of
\non the contact line can
\nbe used temperature from the steam table [17].
\n $θ_r$, which was described
\nWe use the wall temperature as $T_w = 80^\circ \text{C}$, the initial tem-
\nperature as $T_w = 80^\circ \text{C}$, the initial temperature as $T_w = 1 \mu m$, the
\nboundary as $Y_v = 0$, the particle diameter as $d_p = 1 \mu m$, the

temperature from the steam table [17].

We use the wall temperature as $T_w = 80^{\circ}$ C, the initial temperature as $T = 25^{\circ}\text{C}$, the vapor concentration at the open

 $5 \times 10^{-3} \mu s$. ± 1.6) μ m.

initial liquid film height as $y = 5 \mu$ m, the advancing contact

angle as $\theta_a = 90^\circ$, the receding contact angle at the side wall

as $\theta_{sw,r} = 90^\circ$ or 60°, and the receding contact angle at the

bottom

Fig. 4 shows the particle motion with a contact angle of (2.4,3.5, 1.6) m ± ± ^m and (1.2,0.8, 1.6) m. ± ± ^m The liquid-gas interface moves down as the liquid volume decreases with evaporation while the upper particles touch the side walls, as In the case of $\theta_{\text{sw}} = 90^{\circ}$, the lower particles rise up and then seen at $t = 0.3$ ms. Thereafter, the contact line near the touched upper particles is stuck on the side walls and then slips as the other part of contact line keeps moving down. This behavior of interface and upper particle induces a circulated flow in the liquid pool and causes the initially lower particles to rise up slightly and then to be deposited on the side walls. (\pm 2.4,3.5, \pm 1.6) μ m and (\pm 1.2,0.8, \pm 1.6) μ m. The liquid-gas of lower particles is furthe interface moves down as the liquid volume decreases with computations without the upper evaporation while the upper

decreased contact angle, the circulated flow becomes stronger and the lower particles are pushed down and then deposited on the bottom wall, as seen as $t = 2.1$ ms, but the upper particle deposition on the side walls occurs in the same way with the Fig. 5. Particle motion in liquid film evaporation with $\theta_{sw,r} = 60^\circ$ and
initial particle locations of (±2.4,3.5,±1.6) μ m and (±1.2,0.8,
±1.6) μ m.
decreased contact angle, the circulated flow becomes stronger
and pattern of the lower particles is affected by the contact angle at the side walls. .6) μ m.
creased contact angle, the circulated flow becomes stronger
d the lower particles are pushed down and then deposited on
e bottom wall, as seen as $t = 2.1$ ms, but the upper particle
position on the side walls o

The effect of side wall receding angle θ_{SUT} on the motion of lower particles is further investigated through the computations without the upper particles, as presented in Fig. 6. Fig. 5. Particle motion in liquid film evaporation with $\theta_{m_r} = 60^\circ$ and $\frac{1}{3}$ + $\frac{1}{2}$, $\frac{1}{100}$, $\frac{1}{3}$ + $\frac{1}{2}$, $\frac{1}{100}$ and $\frac{1}{2}$ = 60° and initial particle locations of $(\pm 2.4, 3.5, \pm 1.$ touch the side walls, as seen in Fig. 4 including the upper partideposition on the side walls occurs in the same way with
previous case of $\theta_{sw,r} = 90^\circ$. This indicates that the depos
pattern of the lower particles is affected by the contact ang
the side walls.
The effect of side wall cles. When θ_{out} is decreased to 60° and the circulated flow becomes stronger, the lower particles move to the center line and then are pushed down to the bottom wall, as observed in Fig. 5 with the upper particles. This means that the motion of the lower particles is not sensitive to the upper particle motion as long as the upper particles are located near the side wall. creased contact ange, the crituated flow becomes stronger
between the lower particles are pushed down and then deposited on
bottom wall, as seen as t = 2.1 ms, but the upper particle
position on the side walls occurs in t and the over particles are pushed down and then deposited of
deposition wall, as seen as t = 2.1 ms, but the upper particle
deposition on the side walls occurs in the same way with the
previous case of $\theta_{\text{av},\text{v}} = 90^$

interface is further deformed to have a concave shape with the upper particles are at $(\pm 1.2, 3.5, \pm 1.6)$ μ m near the central

Fig. 6. Effect of side wall receding angle of $\theta_{\text{av},\sigma}$ on the motion of Fig. 7. Particle motion in liquid film evaporation with $\theta_{\text{av},\sigma} = 60^\circ$ and lower particles at $(\pm 1.2, 0.8, \pm 1.6)\mu$ without including the

region. As the interface is deformed with evaporation, the upper particles move to the mid plane and then downwards with the interface. The circulated flow along with the upper particle pushes the lower particles outwards to the side wall, as seen at $t = 0.9$ ms. While the upper particles touch on the bottom wall, the lower particles are deposited on the side walls unlike the previous cases depicted in Figs. 5 and $6(b)$ where c the upper particles are initially located near the side wall.

4. Conclusions

A Direct numerical simulation (DNS) method for the particle-fluid and particle-particle interactions was developed by h_{lg} introducing a Level-set (LS) function for tracking the solid region, which was treated as a high-viscosity fluid phase. The \dot{m} DNS method was validated through the 3D computation of M two particles falling in a single-phase fluid whose numerical result was reported in the literature. The DNS method was p extended for 3D particle motion in liquid film evaporation t using two LS functions for tracking the liquid-gas and fluid-

solid and interfaces. The DNS method was demonstrated to be applicable to investigate the particle-interface and particleparticle interactions in liquid evaporation.

Nomenclature-

- *c* : Specific heat
- *d^p* : Particle diameter
- D_{ν} : Diffusion coefficient of vapor in air
- *F* : Fraction function
- *g* : Gravity
- *h* : Grid spacing
- *hlg* : Latent heat of vaporization
- *I^p* : Moment of inertia of a particle
	- : Mass flux across the liquid-gas interface
- *M* : Molecular mass
- **n** : Unit normal vector
- *p* : Pressure
- *t* : Time
- *T* : Temperature
- **u** : Fluid velocity vector (u, v, w)
- **U** : Interface velocity vector
- *V* : Volume
- *x, y, z* : Cartesian coordinates
- **x** : Position vector (x, y, z)
- *Yv* : Vapor mass fraction

Greek symbols

- α : Step function
- θ_a : Advancing contact angle
- θ_r : Receding contact angle
- θ_s : Contact angle on a solid particle
- κ : Interface curvature
- λ : Thermal conductivity
- μ : Dynamic viscosity
- ρ : Density
- σ : Surface tension coefficient
- τ : Artificial time
- ϕ : Distance function from the liquid-gas interface
- ψ : Distance function from the fluid-solid interface
- ω : Angular velocity

Subscripts

- *a* : Air
- *bw* : Bottom wall
- *f* : Fluid
- *g* : Gas
- *I* : Interface
- *l* : Liquid
- *p* : Particle or particle centroid
- *s* : Solid
- *sat* : Saturation
- *sw* : Side wall
- *v* : Vapor
- ∞ : Ambient

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Hochan Hwang received his B.S. degree in Mechanical Engineering from Sogang University in 2013. He is currently a graduate student of Mechanical Engineering at Sogang University, Korea. Mr. Hwang's research interests are in the area of multiphase flow and heat transfer.

Gihun Son received his B.S. and M.S. degrees in Mechanical Engineering from Seoul National University in 1986 and 1988, respectively, and his Ph.D. degree in Mechanical Engineering from UCLA in 1996. Dr. Son is currently a Professor of Mechanical Engineering at Sogang University, Korea. His research interests

are in the areas of heat transfer, multiphase flow and power plant.